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The impact of workload on the ability to localize audible alarms

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Very little is known about people's ability to localize sound under varying workload conditions, though it would be expected to show the typical pattern. A set of eight auditory clinical alarms already known to have relatively high localizability (the ease with which their location is identified) when tested alone were tested in six conditions where workload was varied. Participants were required to indicate the location of a series of alarms emanating at random from one of eight speaker locations. Additionally, they were asked to read, carry out mental arithmetic tasks, be exposed to typical ICU noise, or carry out either the reading task or the mental arithmetic task in ICU noise. Performance in the localizability task was best in the control condition (no secondary task) and worst in those tasks which involved both a secondary task and noise. The data does therefore demonstrate the typical pattern of increasing workload affecting a primary task in an area where there is little data. In addition, the data demonstrates that performance in the control condition results in a missed alarm on one in ten occurrences, whereas performance in the heaviest workload conditions results in a missed alarm on every fourth occurrence. This finding has implications for the understanding of both 'inattentional deafness' and 'alarm fatigue' in clinical environments.

Keywords: auditory alarms; clinical alarms; clinical safety; patient safety; auditory processes

INTRODUCTION

The many problems associated with clinical alarms are well documented in the literature. Key among the problems is the issue of 'alarm fatigue' – an often-noted, but not clearly understood, description of a problem which stems from a combination of high false alarm rates, meaningless or difficult-to-understand alarms, noise, excessive monitoring, and other issues surrounding good practice (Cvach, 2012; Deb & Claudio, 2015; Drew et al, 2014; Kristensen, Edworthy & Ožcan, 2017; Sendelbach & Funk, 2013; Welch et al, 2011; Whalen et al, 2014). Not least of the problems associated with audible alarm signals specifically is that their design is very far from ideal, with alarm signals typically found to be difficult to learn and remember (Atyeo & Sanderson, 2015; Edworthy, Page et al, 2014; Lacherez et al, 2007; Sanderson et al, 2006; Wee & Sanderson, 2008). The reason for this is that clinical alarms are often tone-like, akin to short melodies, largely abstract (where the sounds have little or no relation to their referents) and are often very similar to one another, thus proving to be difficult to learn and retain.

Many accounts of missed alarms exist in the reporting literature, and fatalities and other serious incidents are often attributed to 'alarm fatigue' because the nurse or clinician did not hear, or reports not having heard, the relevant alarm (e.g. Drew et al, 2014). The reason for missing the alarm is sometimes cited as being associated with the nurse's state at the time – for example, they may have been tired, at the end of a shift, may have been overwhelmed by alarms, may have some hearing loss etc. Just as likely, the reason for the missed alarm has something to do with the relationship between the alarm and the nurse in psychoacoustic, cognitive, or broader human factors, terms. The four most obvious explanations would be that the particular alarm is usually false, and so the nurse has tuned it out (this is commonly thought of as the key element of alarm fatigue as the relationship between false alarm rate and response is well documented (Bliss et al, 1995; Bliss & Dunn, 2000); the alarm could have been masked by other alarms or noise and so be inaudible to the nurse (Hasanain et al, 2017; Patterson,1982; Laroche et al, 1991); the alarm could be difficult to localize and hence failed to draw attention to the particular location of the problem (Alali, 2011; Catchpole et al, 2004; Edworthy et al, 2017; Vaillancourt et al 2013); or the nurse was busy attending to other tasks (i.e. multitasking) and so her attention was diverted from alarm sounds to other tasks, an auditory phenomenon often referred to as 'inattentional deafness' (Dalton & Fraenkel (2012); Dehais et al, 2014; Macdonald & Lavie (2011); Raveh, & Lavie, 2015); Murphy & Green, 2015). Here, if a person is doing more than one task, then they have to divide their mental resources between them and therefore this may exceed that person's capacity both within and across sensory modalities (Wickens, 1991). Inattentional deafness probably lies within the domain of problems which ensue when workload is high, or where cognitive capacity is stressed in one way or another.

Many factors conspire to confuse the hearer about the nature of alarm; what it is, where it is coming from, whether there was an alarm or not (as the clinician might have been doing a couple of other things at the same time and so is unsure), the physical and mental state of the hearer, and other factors. The design of the alarm could in principle help the hearer, though this does not always happen. As well as being difficult to learn and retain, the localizability of alarms could also be improved. Although the mechanisms concerned with localizability by the ear and brain are complex (Blauert, 1997) we do know that by and large sounds are easier to localize if they are harmonically complex, making white noise the most localizable sound. By contrast, clinical alarms tend to be harmonically very simple, often relying on one or two harmonics for detection, meaning that their localizability will not have been optimized. There are many clinical environments (for example a multibed ICU) where automatic and accurate localization (through the operation of mechanisms of the ear and the brain) would be of benefit.

In an earlier study (Edworthy et al, 2017) we designed five sets of audible alarms using different design principles, and showed that the learnability and localizability (except for localizability in one case, which was expected and predicted) of our new designs outperformed the audible alarms currently supporting an international clinical device safety standard (IEC 60601-1-8, IEC (2012)). In the localizability study (Edworthy et al 2017, Experiment 2), the mean localizability accuracy for the best-performing alarm set, the 'auditory icons plus ident' set, was just above 0.9 (out of 1). For the worst-performing set, the current IEC sounds, overall localization accuracy was 0.74 (out of 1). This means that in the IEC condition participants were mislocalizing a quarter of the alarms (one alarm in every four) whereas in the best-performing condition, they were mislocalizing only one in 10 alarms. This is meaningful at a practical level.

In Edworthy et al 2017 participants were simply asked to identify from which of eight speakers an alarm was transmitted in each trial. In the study here, we increase the difficulty of the task by adding some secondary tasks, and noise, and gauge their effects on localizability.

The practical focus of this project is to update the audible alarms currently recommended by IEC 60601-1-8. On the basis of the work described in Edworthy et al (2017), the ‘auditory icon plus ident’ set of alarms has been selected for further testing and development through consultation and agreement with the body charged with recommending the specific details of the updates proposed for 2019, when the new version of the standard is published (this is an IEC alarms joint working party). The study described here represents one arm of this further testing, exploring the effect of workload and noise on people’s ability to localize this set of alarms, using the localization paradigm used in Edworthy et al (2017). As workload affects ability on most other tasks, including auditory tasks, we would expect it to influence people’s ability to localize an alarm sound, so we would expect that a participant’s localization ability should be reduced when they are performing one or more secondary tasks when compared with a simple localization task. In our study we introduce either one or two secondary tasks. Most simply, we would expect the addition of secondary tasks to degrade performance in our localization task. There are few studies which consider this issue so our work adds to knowledge in this area as well as providing further testing of the alarms aimed at the update of the relevant standard.

METHOD

Participants

Two hundred and seven participants were recruited to participate in this study (175 women, 32 men, M_{age} = 20.78, age range: 18-50 years). Most were psychology undergraduates at Plymouth University. Recruitment took place using the Plymouth Psychology participation pool and participants received one participation point in exchange for completing the 30-minute study. All participants stated that they had normal, or corrected to normal, hearing. Details of participants' age and gender were also obtained (See Table 1). No other demographic information was recorded.

Condition	Number of participants	Age range (SD)
Control	23	18-50 (5.15)
ICU Noise	34	18-42 (4.92)
Reading	33	18-46 (5.44)
Mental arithmetic	49	18-50 (6.50)
Reading plus noise	35	18-35 (4.08)
Mental arithmetic plus noise	33	18-44 (4.60)

Table 1: Number of participants in each condition and age range for each condition

Materials and Design

The overall design of the study was 6 (task, between-subjects) x 8 speakers (within-subjects) x 8 alarm sounds (within-subjects). Each participant was required to detect and respond to the occurrence of alarms spaced around them in a circle, while performing a secondary task, either in noise or in quiet. In the control condition, they simply responded to the alarms by indicating the speaker from which they thought the alarm had sounded. The details of the experimental conditions can be seen in Table 2. In the five experimental conditions, participants were exposed to either: a repeating 2-minute loop of ICU noise; a reading task; a mathematics task; a reading task plus the ICU noise loop; or the mathematics task plus the ICU noise loop; in a between-subjects design. Participants were not told the names and functions of the alarms as localizability and performance of the secondary task was our focus.

A set of eight auditory alarms previously tested for learnability and localizability (with no secondary tasks) were used as the stimuli, and can be seen in Table 3 (Edworthy et al, 2017). The sounds were normalised for loudness and were presented at approximately 60-63 dB(A), measured through 3 10-second bursts of sound at 70 inches from each of the speakers. The sounds varied from 2-3 seconds in length. Each of the sounds consisted of an auditory icon (as listed in Table 3) plus an 'ident', which was the general alarm indicated in Table 3, an abstract sound of fixed length. For the general alarm, only the ident was used.

Control	ICU noise	Reading	Mathematics	Reading + ICU Noise	Maths + ICU Noise
Ps responded to the location of alarms only	As in Control, plus Ps were exposed to a 2-minute repeated loop of ICU noise through surround sound presented at approximately 60dB	As in Control, plus Ps were required to read text on paper which was grammatically correct but nonsensical	As in control, plus Ps were required to complete a series of mental arithmetic tasks presented on paper	Control, plus Reading, plus ICU Noise	Control, plus Mathematics, plus ICU Noise

Table 2: The six experimental conditions

Apparatus

Eight identical tripods were placed around a central point (where the participant would be seated), each with a small speaker attached to it (EasyAcc mini portable model LX-839, output 3W), in the format shown in Figure 1. The speakers were calibrated to a comfortable listening level of approximately 60-63 dB (A) at a distance of 70 inches from each speaker. Participants sat in the middle of the room, where they sat at a table on which there was a tablet presenting a visual layout of the speakers in a circle. A radio button represented each of the eight speakers in the appropriate position. Participants were required to press the relevant radio button as each alarm was presented.

Function of Alarm	Alarm Characteristics
General	A burst of three regularly spaced pulses each of 75ms in length, followed by a gap of 0.15 seconds, followed by two further pulses of 75ms on a fixed pitch (c c c – c c) The whole 5-pulse unit then repeated; then the whole 10-pulse unit repeated after approximately one second
Power down	The sound of a hedge trimmer failing to start
Cardiovascular	A 'heartbeat' sound with no discernible frequency. Six pulses formed from 3 2-pulse units indicating 3 heartbeats
Perfusion	A 'water bubbling' sound, 2 pulses each approximating 1.5 seconds in length
Drug Administration	The sound of a continuously rattling 'pillbox'
Oxygen	The sound of an aerosol, 4 pulses each spaced 600ms apart
Ventilation	The sound of a single deep breath out
Temperature	The sound of 'frying on a stove top'

Table 3: Auditory icon alarms used in the study. Each alarm (other than the General alarm) was played simultaneously with the general alarm, in an 'auditory icon plus ident' design, the general alarm serving as the ident

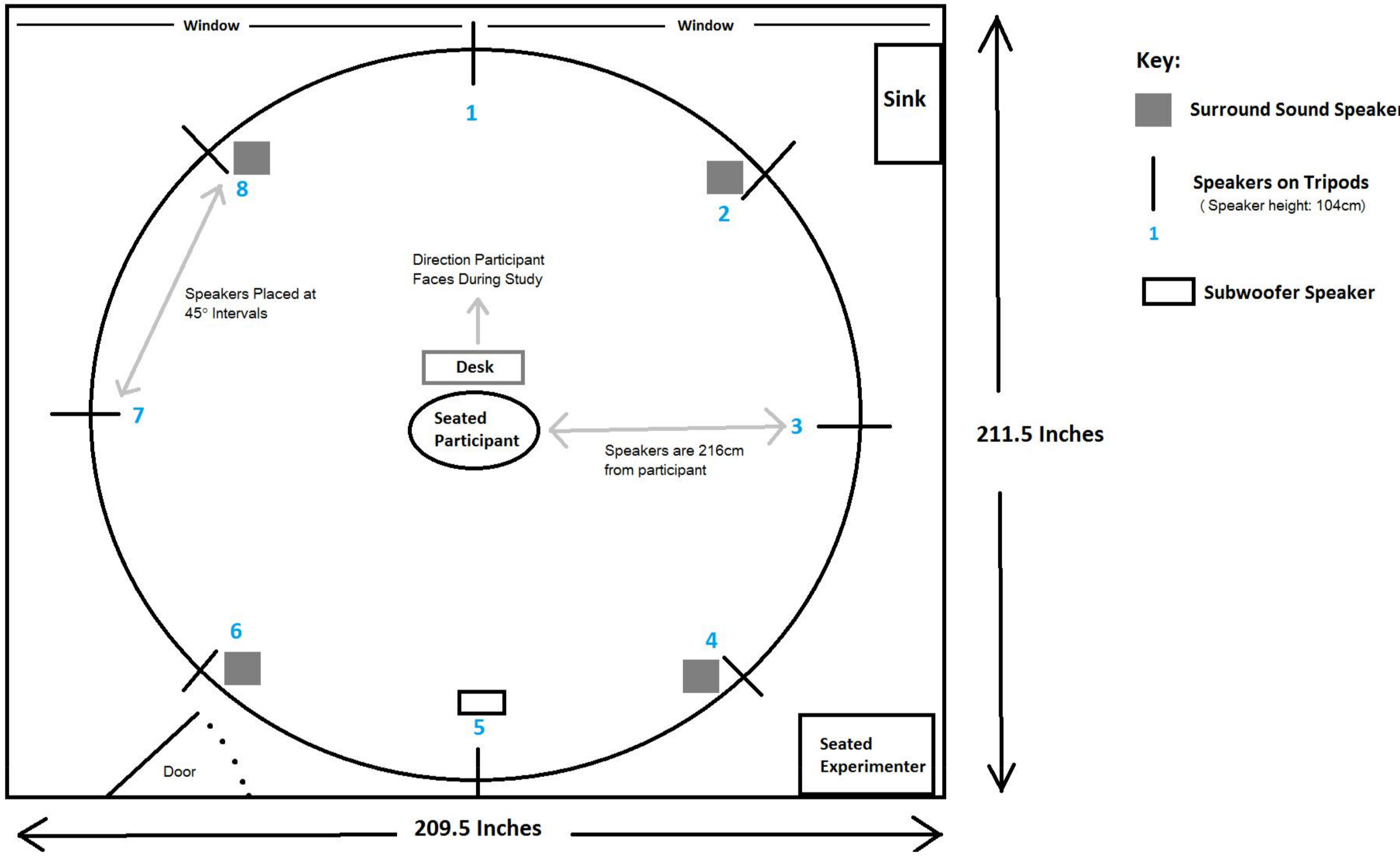

Figure 1: Layout of the room where the study took place

The participant responded on a Linx 10, windows eight tablet (Intel Atom 23735F, 1.33 GHZ, RAM: memory 2 GB) with the volume set at 50, which was placed on the desk. The participant was seated at the desk, in the middle of the circle of speakers. The experiment was run using a program written in Visual Basic (2013). A custom-made input box was also utilised, containing eight channel analogue switches. This box routed audio sounds to one of the eight speakers in each trial (on a block-random basis), and was controlled by a microcontroller receiving USB commands from the program on the Linx 10 tablet. All speakers were connected using 10m 3.5mm jack extension with stereo wires.

Procedure

Participants were seated in the centre of the room, surrounded by eight speakers on tripods (which played the alarms), and four surround sound speakers (which played the ICU noise) (See Figure 1). After a few practice trials, participants were presented with eight blocks of eight alarms, with each alarm being heard once in each of the eight positions. Their primary task was to identify the location of the alarm by selecting the corresponding circle on the tablet. If they were not sure, they were asked to indicate the location as closely as they could estimate. Participants were not given feedback as to whether they had provided a correct response. During the whole of the experimental task, participants were also required to participate in their allocated secondary task condition. This involved nothing else (control); carrying out the task while being exposed to typical ICU noise; having to read a document; having to complete some mental arithmetic tasks; having to both read and be exposed to ICU noise; or having to complete mental arithmetic tasks whilst also being exposed to ICU noise.

Results

Condition x Speaker

Figure 2 show the means for each of the six conditions in each of the eight speaker positions

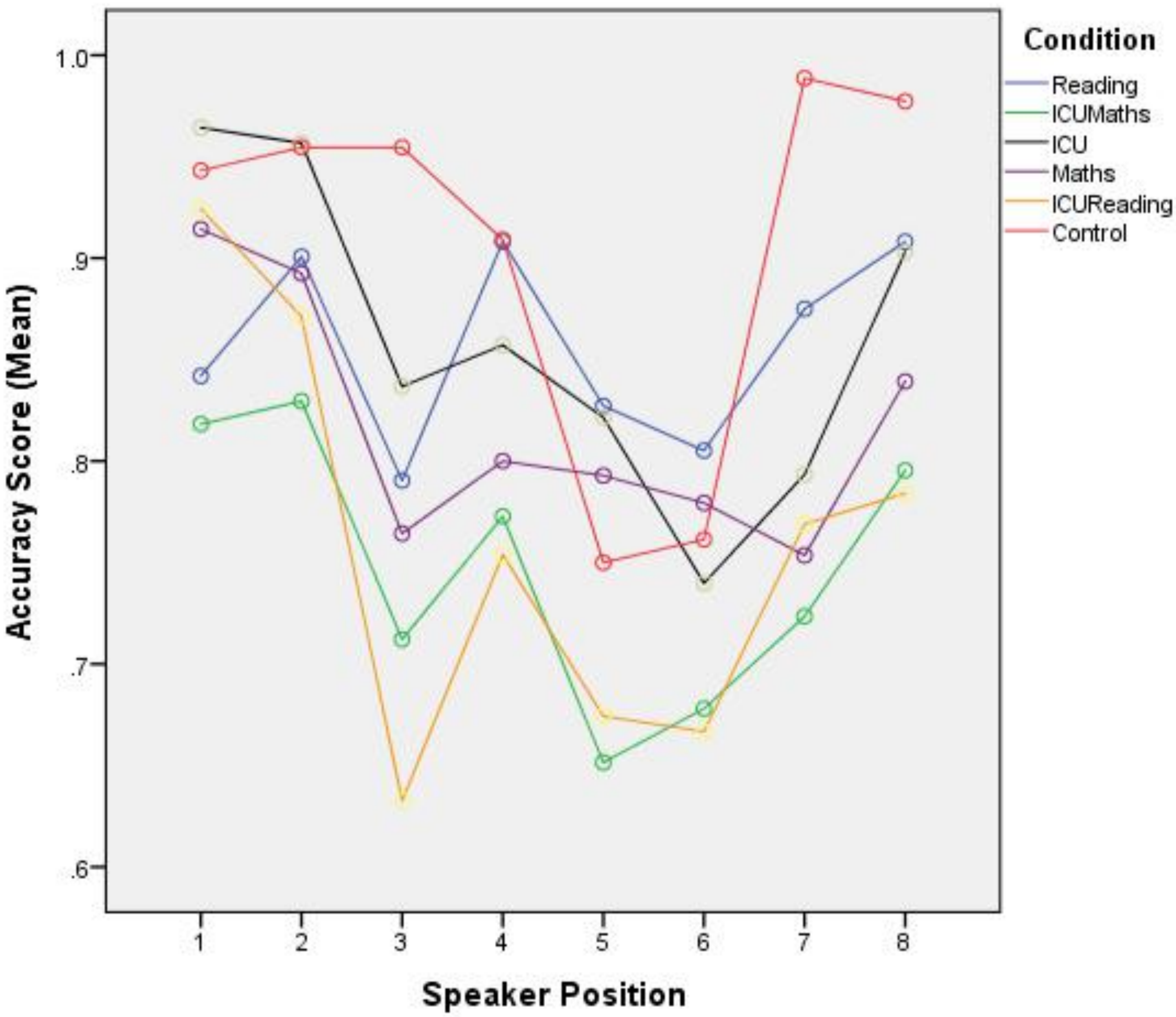

Figure 2: Means for each of the Condition x Speaker conditions

Tables 4 and 5 show the means and standard deviations for each of the six conditions (Table 4) and each of the eight speakers (Table 5)

Condition	*M*	*SD*
Reading	.86	(.35)
Maths	.82	(.39)
ICU	.86	(.35)
ICU Reading	.76	(.43)
ICU Maths	.75	(.43)
Control	.90	(.29)

Table 4: Mean scores and SDs for each of the six experimental conditions

Speaker Position	*M*	*SD*
1	.90	(.30)
2	.90	(.30)
3	.77	(.42)
4	.83	(.38)
5	.76	(.43)
6	.74	(.44)
7	.80	(.40)
8	.86	(.35)

Table 5; Mean scores and SDs for each of the eight speaker positions

A Condition x Speaker ANOVA on the accuracy scores revealed a statistically significant main effect for condition [*F* (5, 12432) = 44.52, *p* < .001], a main effect for speaker position [*F* = (7, 12432) = 35.37, *p* < .001] and a significant interaction between condition and speaker position [*F* (35, 12432) = 3.31, *p* < .001] (Figure 2). Table 6 shows which conditions are significantly different from one another, and Table 7 shows which speaker locations are significantly different from one another.

	Control	Noise	Reading	Maths	Noise + Reading	Noise + Maths
Control		*	*	**	***	***
Noise				***	***	***
Reading				**	***	***
Maths					***	***
Noise + reading						
Noise + maths						

Table 6: Significant differences between tasks. In all instances the score in the condition in the left-hand rows was higher than that represented in the columns
* p < 0.05, ** p < 0.01, *** p < 0.001

Speaker	1	2	3	4	5	6	7	8
1			**	**	**	**	**	*
2			**	**	**	**	**	*
3				** ↑				**↑
4					**	**		
5								**↑
6							**↑	**↑
7								**↑
8								

Table 7: Significant differences between speaker conditions. For all comparisons performance for the speaker indicated in the left-hand rows is higher than the speaker indicated in the columns, except where there is a ↑ indicating that performance for the speaker in the column was higher. * p < 0.05, ** p < 0.001

Other comparisons

For this study we were particularly interested in the relationship between the tasks and the speakers, and only secondarily interested in the individual sounds themselves as they are a set with a particular design remit and behave in slightly different ways from one another. A 6 x 8 Condition x Sound ANOVA demonstrated a statistically significant main effect for condition [F (5, 12432) = 44.13, p < .001], a main effect for sound [F (7, 12432) = 6.07, p < .001] and a statistically significant interaction between these two [F (35, 12432) = 2.14, p < .001].

An 8 x 8 Speaker x Sound revealed a statistically significant main effect for sound [F (7, 12416) = 8.38, p < .001], a statistically significant main effect of speaker [F (7, 12416) = 39.81, p< .001], as well as a significant interaction between them [F (49, 12416) = 2.20, p < .001]. These effects are interesting from an alarm design point of view but not central to the arguments presented in this paper.

DISCUSSION

Our results are interesting both in terms of relative performance (the way in which performance varied with condition and speaker) and absolute performance (the overall localization rate). Our results show that as load (workload) increases, performance on the localization task declines. This is not surprising and would be expected for almost any task in which the burden for the participant varies. The results obtained show that the easiest task was the localization of the alarms without any secondary burden, as would be expected. The degradation in performance on the localization task was approximately equivalent (not statistically different) for the ICU noise and the reading conditions, suggesting that they provide similar levels of disruption. Of course, had the noise been louder or quieter that would have rendered the localization task harder or easier – if the noise had masked the alarms this would have made the task very much harder, but our aim in this task was to provide a reasonable level of realistic noise where that noise performed as a stressor rather than a masker. Our results show that the presence of noise leads to some decline in performance relative to there being no noise.

Performance in the localization task dropped significantly further in the mathematics task, and then further in the two conditions where participants were expected to carry out two tasks in addition to the localization task, again demonstrating that as workload increased, performance in the localization task decreased. That the mathematics task led to more decline than the reading task might be due to the fact that participants had to engage more in the mathematics task – they had to write down the answers – than they did in the reading task. It would be interesting to see how a different kind of verbal task, such as talking, might affect performance (see Edworthy et al, 2013). One key take-home message from our study is that whereas the performance level in the control condition represented the missing of one in ten alarms, in the most difficult conditions (noise and a reading or arithmetic task), performance had dropped to the missing of one in four alarms. Increasing workload of itself therefore affects people's ability to locate the direction of an alarm sound.

We did not ask participants how many alarms they thought they had heard during the study, nor did we probe them further when an alarm sounded but no response was given. Thus we do not know in this study whether missed or wrongly identified alarms were due to an attentional failure in an inattentional deafness sense, or that participants made more errors in the task, though our data suggests a combination of both. We do not anticipate that alarms were masked by the noise (where participants were exposed to noise) because of the way the speakers were set up, and our piloting of the study suggested that alarms coming from all eight speakers were audible.

Another striking feature of these results in comparison to those of Edworthy et al (2017) is that performance even in the 'ICU noise + …' conditions, people's performance in localizing these alarms was no worse than their ability to localize the current IEC alarms when no secondary tasks were involved. Thus our second important take-home message is that the alarms being benchmarked in this study, which are intended for incorporation in a future standard, because they are designed better and are a priori easier to localize, have such a premium in terms of improved localizability that they perform at the same level as the current alarms only when heard both in noise and when participants are trying to either read or do calculations. We consider this a significant premium and feel it demonstrates the extent to which the design of the alarm can ease the task of the hearer.

The data for the individual speakers is similar for that obtained by Edworthy et al (2017) in that performance generally declined as the sound moved from the front, around the side and the back of the participant and then improved again as the sound moved towards the front of the participant (though performance was better overall for Speaker 4 than a speaker further forward, 3). This pattern of performance is typical for a detection task and though there is an interaction between speaker and task this interaction is of modest size, with the general pattern of our previous study still clear (Figure 1).

In summary, our results add to the very small body of literature showing how workload can influence the ease with which the location of a sound can be identified, and adds to the understanding of 'alarm fatigue' in terms of variables which can influence people's ability or capability in detecting audible alarms.

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HIGHLIGHTS

- This paper is one of very few studies showing the effect of workload on people's ability to localize sound
- Increased workload increases people's tendency to mislocate auditory alarms
- The effect of adding two tasks to a control condition is to increase the miss rate from 1 in 10 alarms to 1 in 4